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Mechanical efficiency of rowing a single scull

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To determine the mechanical of rowing, oxygen uptake and mechanical work rate were measured during rowing a single scull under windless conditions. Steady-state pulmonary oxygen uptake was determined as a function of boat velocity (v (m·s^{-1})) in 5 subjects. Oxygen uptake (l·min^{-1}) increased as 0.065 $v^{2.99}$. Workrate in two subjects was determined as a function of v by measuring the force applied to the oar and its angular velocity. Work rate (w) was expressed as 3.85 $v^{3.25}$. From these equations, mechanical efficiency (%) was expressed as 17 $v^{0.262}$. Thus, mechanical efficiency increased from 20% at 2 m·s^{-1} to 24% at a boat velocity of 4 m·s^{-1}.

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Key words: oxygen uptake; anaerobic energy; work rate

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Due to the difficulty of measuring oxygen uptake by the Douglas bag method while rowing in a shell, the metabolic cost of rowing has been determined on an ergometer (1, 2) or during rowing in a tank (3-5). Only one study has measured oxygen uptake during rowing on the water (6).

With the development of a reliable portable telemetry system for oxygen uptake ($\dot{V}_{O_2}$)(7, 8), it has become much easier to measure $\dot{V}_{O_2}$ in a rowing shell. We used such a portable $\dot{V}_{O_2}$ system to determine the relationship between $\dot{V}_{O_2}$ and boat velocity in a single scull. The relationship between work rate and boat velocity was also assessed. Thus we were able to calculate the mechanical efficiency of rowing on water.

Material and methods

Experiments were performed using a single scull on a windless rowing course with no stream. $\dot{V}_{O_2}$ during rowing a single scull at various constant velocities was measured using a K2 system (Cosmed, Rome, Italy). Five varsity scullers (171.8 ± 3.4 cm, 69.8 ± 4.4 kg, 21.4 ± 0.8 years; mean ± SD) participated in this study with informed consent. They were instructed to row 3500 m and to increase boat velocity every 700 m. Consequently, the subjects sculled at 5 submaximal velocities at a pace that was kept as constant as possible by the rowers' own judgement. The K2 apparatus was placed on the subjects before launching, and $\dot{V}_{O_2}$ at rest was measured for 5 min. While rowing $\dot{V}_{O_2}$ was measured every 15 s and the mean value for last minute at each velocity was noted. Boat velocity was determined on the last 300 m of each step. The metabolic cost of rowing was taken as $\dot{V}_{O_2}$ rowing – $\dot{V}_{O_2}$ rest. The exponential curve between the metabolic cost of rowing and boat velocity was calculated by the least square method:

$$\dot{V}_{O_{2net}}(\text{l·min}^{-1}) = av^{b} \qquad (1)$$

where a and b are constants and v is boat velocity in m·s^{-1}.

In 2 of the scullers (A: 172 cm, 68 kg; B: 171 cm, 78 kg) the relationship between work rate and boat velocity was also determined. They were instructed to row 1200 m and to increase boat velocity every 200 m, the last 200 m representing maximal rowing. Boat velocity was calculated from the time from 50 to 150 m in each step. Work rate was determined by the 2 strain gauges mounted to the loom between the handle and the crutch. Each strain gauge was calibrated by applying known weight to the handle of the scull. Angle of the crutch was measured by an electrical goniometer (Penny & Giles, Blackwood, UK) mounted on the portside of the shell (Fig. 1). Strain and angle data was A/D converted and sampled at a rate of 50 Hz (Fig. 2). Data for 10 strokes in each step were analyzed. Work rate was calculated as:

$$\text{Work rate (W)} = \frac{SR}{60} \times \sum_{\text{stroke}=1}^{10} \left(2 \int_{\text{catch}}^{\text{finish}} FL \frac{d\theta}{dt}\, dt\right) \qquad (2)$$

where F = force (N), θ = angle of crutch(degree), L = inboard length of the scull(m) and SR = stroke rate (stroke · min^{-1}).

Work rate was calculated corresponding to each applied boat velocity by the least square method:

$$\text{Work rate (W)} = k\,v^{n} \qquad (3)$$

where k and n are constants.

Mechanical efficiency was calculated from eq. (1) and (3) assuming a value of 4.2 kJ · l^{-1} for the caloric equivalent for O_2.

$\dot{V}_{O_2}$, ventilation (VE) and heart rate (HR) were also measured using K2 during 1500 m at maximal intensity in the 2 subjects in whom work rate was determined. Data were recorded every 15 s. At the same time an observer timed the rower every 100 m. $\dot{V}_{O_2}$ requirement ($\dot{V}_{O_2req}$) correspondent to each boat velocity was extrapolated from submaximal velocities (eq. (1)). Oxygen deficit during race rowing was determined by subtracting $\dot{V}_{O_2net}$ from the estimated $\dot{V}_{O_2req}$ (9).

Results

$\dot{V}_{O_2net}$ in 5 subjects increased curvilinearly with boat velocity accordingly to the equation.

$$\dot{V}_{O_2net}\ (l \cdot min^{-1}) = 0.065\ v^{2.99}\ \text{(Fig.3)} \qquad (4)$$

Also work rate increased curvilinearly with boat velocity.

$$\text{Work rate (W)} = 3.85\ v^{3.25}\ \text{(Fig.4)} \qquad (5)$$

By substitution the relationship between $\dot{V}_{O_2net}$ and work rate was obtained:

$$\dot{V}_{O_2net}\ (l \cdot min^{-1}) = 0.019\ \text{(work rate)}^{0.92} \qquad (6)$$

Consequently, mechanical efficiency tended to increase with work rate (Fig. 5).

Furthermore, from eq. (4) and (5) mechanical efficiency could determined as a function of boat velocity:

$$\text{Mechanical efficiency (\%)} = 17\ v^{0.262} \qquad (7)$$

This equation calculates a mechanical efficiency of 20%, 23% and 24% at boat velocities of 2, 3 and 4 m·s^{-1}, respectively. Fig. 6 indicates that mechanical efficiency of rowing increased more clearly with boat velocity than with work rate (Fig. 5).

Changes in $\dot{V}_{O_2}$, VE, HR and boat velocity during race rowing for each subject are shown in Fig. 7. These physiological parameters levelled off approximately 2 min after the start. $\dot{V}_{O_2req}$ was calculated by substituting each boat velocity into eq. (4). Changes in $\dot{V}_{O_2req}$ and $\dot{V}_{O_2net}$ are shown in Fig. 8; the area A represents oxygen deficit and the area B aerobic energy consumption. Aerobic and anaerobic energy consumption were 350 kJ and 100 kJ for subject A, and 330 kJ and 140 kJ for subject B, respectively. The ratio of aerobic energy in total energy requirement was low (20 and 32%) just after start, but increased gradually and reached at relatively high constant value (about 90%) in the middle part.

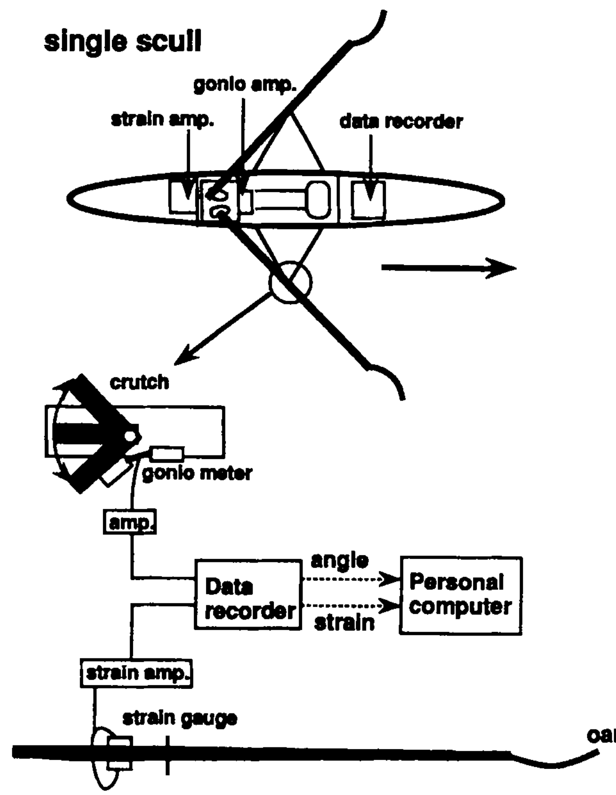

Fig. 1. Schematic illustration of work rate measurement in actual rowing. Force applied to the oar was measured using strain gauges and the angle displacement using an electrogoniometer.

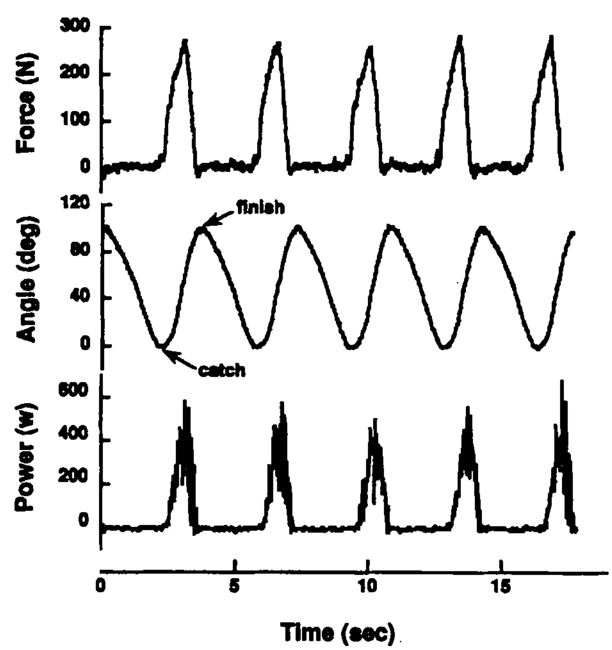

Fig. 2. Force, angle, and stroke power during five strokes. Stroke power was determined as the product of force times angular velocity. Angular velocity was calculated by differentiating the angle with respect to time.

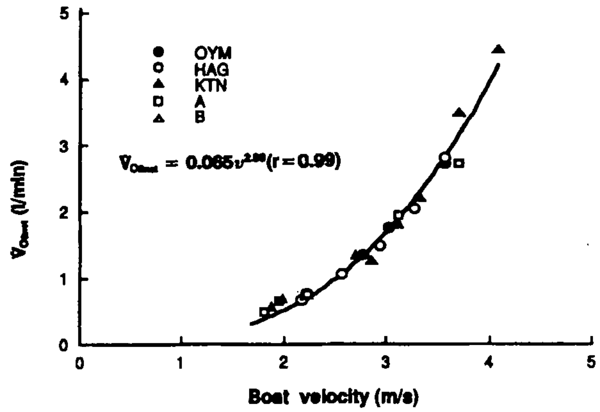

Fig. 3. Boat velocity and $\dot{V}O_{2net}$. Solid line is the regression curve.

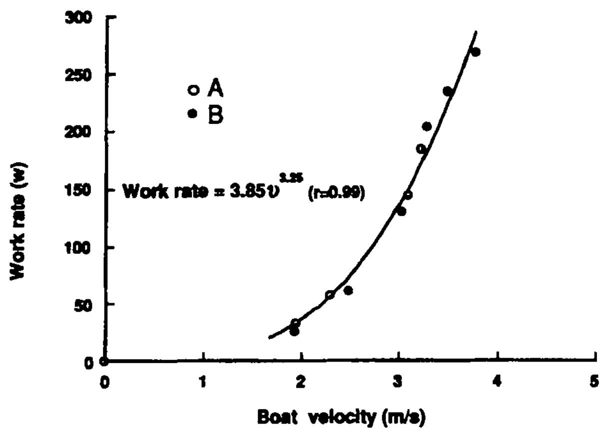

Fig. 4. Boat velocity and work rate. Solid line is the regression curve.

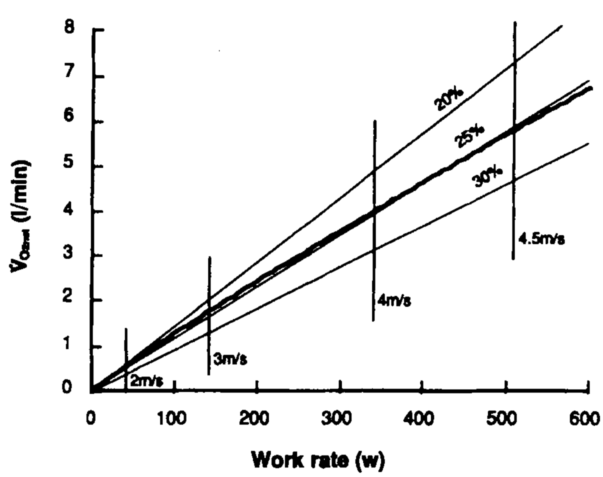

Fig. 5. $\dot{V}_{O_{2net}}$ and work rate. The isoefficiency lines are inclined and the vertical lines are the work rate corresponding to boat velocity.

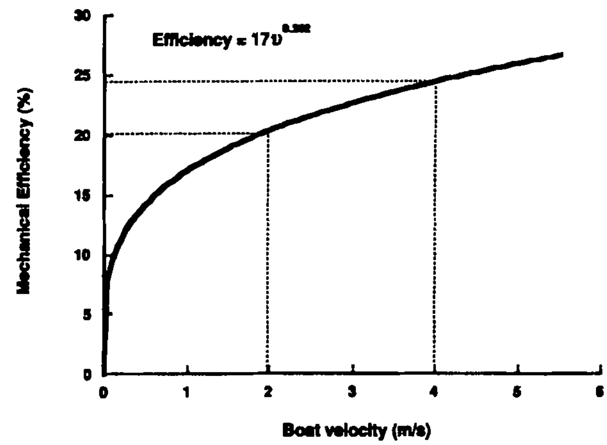

Fig. 6. Mechanical efficiency expressed as a function of boat velocity. Mechanical efficiency increased with boat velocity, and it was 20% at 2 m/s and 24% at 4 m/s.

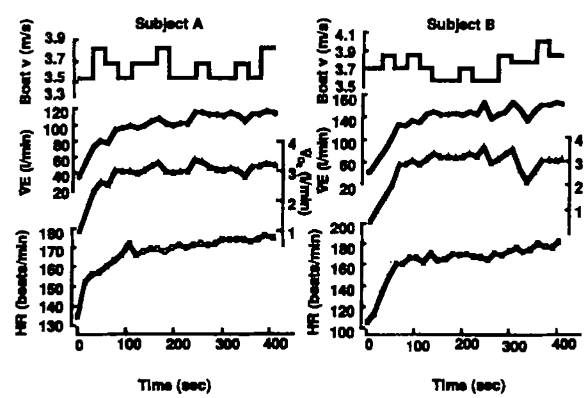

Fig. 7. Changes in $\dot{V}_{O_2}$, $\dot{V}E$, HR and boat velocity during race rowing with time. All physiological parameters reach at the maximal level about 100 s after start.

Discussion

Boat velocity-$\dot{V}_{O_2}$ relationship

Jackson & Secher (6) reported that the relationship between boat velocity and $\dot{V}_{O_2}$ was linear or slightly curvilinear while it was indicated that $\dot{V}_{O_2}$ could be described as a power function of boat velocity, i.e., $\dot{V}_{O_2} = 0.1944\ v^{2.21} + 0.28$ in a single scull by Secher (10). The value of $\dot{V}_{O_2}$ in this study was similar to or slightly lower than Secher's result at low boat velocity, but at a relatively high boat velocity the discrepancy becomes larger; 2.1 *vs* 2.48, 4.4 *vs* 4.44 and 8.4 *vs* 7.09 ($l \cdot min^{-1}$) at 3, 4, and 5 $m \cdot s^{-1}$, respectively. The data reported by Secher involved the values during high-intensity rowing at which the contribution of anaerobic energy consumption could not be ignored. On the other hand, our results were acquired by measuring $\dot{V}_{O_2}$ during steady-state rowing in which anaerobic energy consumption was negligible. This might partly cause the large discrepancy at a high boat velocity. Also, it is a problem to extrapolate va-

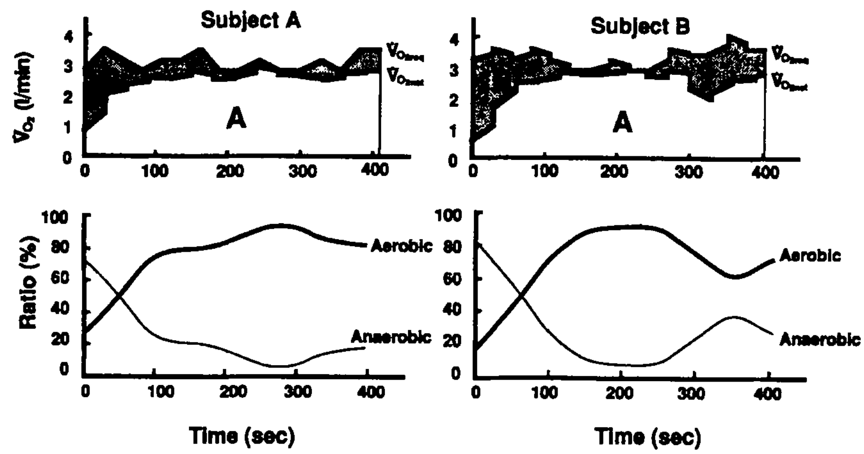

Fig. 8. Ratio of anaerobic energy consumption to the total energy requirement. The top graph indicates $\dot{V}_{O_{2req}}$ and $\dot{V}_{O_{2net}}$. A, aerobic energy consumption; B, anaerobic energy consumption. Note that the lines of the bottom graph are smoothed by freehand.

lues to high-intensity from low-intensity exercise (11). Yet, assuming that the calculated relationship is correct even at high boat velocities, eq. (4) can be used to determine the total energy requirement to propel a boat.

Boat velocity-work rate relationship and mechanical efficiency

The work rate increased in proportion to the approximately third power of the boat velocity. This result is reasonable, considering that work rate is the product of the resistance force applied to the hull at a given boat velocity. Resistance force increases with the second power of the boat velocity(12). Similarly, work rate increased as 2.8 $v^{3.2}$ in the study by di Prampero et al. (5) and as 4.7 $v^{2.95}$ in the study by Celentano et al.(13).

Using eq. (5), the value of work rate is calculated to be 137, 349, and 720 W at 3, 4 and 5 m · s^{-1}, respectively. Hagerman et al. (2) report that work rate during 6 min of maximal ergometer rowing was 363 W for elite rowers. Compared with their result, the present value of 720 W is twice as large, although it is possible to row a boat velocity of 5 m · s^{-1} in international competitions. Since boat velocity in the present study was less than 4 m · s^{-1}, it should be expected that our calculations are inaccurate at high velocities.

Mechanical efficiency could be determined as a function of boat velocity (eq. (7)). This is the first report on mechanical efficiency during actual rowing. It was above 20% at very low velocity and reached 25% at a high velocity. This value is larger than acquired by ergometer rowing (1, 2), and in a rowing tanks (3-5). On the other hand, it was similar to the value of actual rowing acquired from a HR-$\dot{V}_{O_2}$ relationship (5). Consequently, the mechanical efficiency appears to be larger in actual rowing than in simulated rowing (5).

The relationship between $\dot{V}_{O_{2net}}$ and work rate was slightly curvilinear and mechanical efficiency increased with work rate (Fig. 5). Yamamoto et al. (4) and di Prampero et al. (5) also reported that mechanical efficiency increased with work rate. This tendency would be attributed to the characteristic of rowing.

di Prampero et al. (5) explained that efficiency increases with work rate relate to the fact that the oar does not move in a straight line, hence the force component perpendicular to the long axis of the boat is not useful to boat propulsion. The mechanical work of this component was independent of work rate. Accordingly, the ratio of effective work increased with work rate. However, comparing Fig. 5 and Fig. 6, the increase in mechanical efficiency was more influenced by boat velocity than by work rate. During rowing the boat velocity fluctuates because the rowing cycle has a stroke and a forward phase. Mechanical efficiency-increase is caused by the fluctation-decrease with stroke rate, i.e., boat velocity (14, 15).

Energy expenditure in race rowing

The estimated contribution of the anaerobic metabolism to race rowing over 1500 m was 22% and 29% of the total energy requirement on subjects A and B, respectively. The simulation of race rowing in this study covered only 1500 m while actual race rowing is most often performed over 2000 m. Considered that the duration of the actual race is longer than that of this simulation, the contribution of anaerobic energy is lower. The values obtained in this study were somewhat lower than the value of 30% estimated by Hagerman et al. (2) based on oxygen debt. It should be considerėd that the present measurements were performed in the off-season, during which the rowers do not perform anaerobic training. Actually the average velocity at which the subject A rowed was low, compared with the average velocity of the previous season (3.7 m · s^{-1} *vs* 4.2 m · s^{-1}).

In this study, the changes in the ratio of anaerobic energy consumption to the total energy consumption from start to finish could be determined (Fig. 8). Anaerobic energy was consumed primarily at the start and during the last spurt. In the middle part its ratio was below 10%.

We tried to determine the ratio of anaerobic energy according to the race result of the 1991 Japan lightweight championship. Two scullers rowed the middle part (500-1500 m) in 3'47" and 3'53" in the final competition during windless conditions. These results show that the estimated $\dot{V}_{O_{2req}}$ are 5.47 l · min^{-1} and 5.36 l · min^{-1}. On the other hand, the scullers' $\dot{V}_{O_{2max}}$ was reported to be only 4.89 l · min^{-1} and 4.67 l · min^{-1}, respectively. Hence the ratios of anaerobic energy are estimated to be 18% and 20% assuming resting $\dot{V}_{O_2}$ to be about 0.4 l · min^{-1}. These values are larger than those estimated from the results of this study.

It is assumed that the contribution of anaerobic energy in race rowing is approximately 20% in the excellent scullers. The equation that expresses the relationship between $\dot{V}_{O_{2max}}$ and boat velocity is:

$$\dot{V}_{O_{2max}}\ (l \cdot min^{-1}) = 0.8 \times 0.065\ v^{2.99} + \text{resting}\ \dot{V}_{O_2} \quad (8)$$

Thus the $\dot{V}_{O_{2max}}$ required to row 1000 m in the middle part of the race in 3'20" can be estimated to be approximately 6.8 l · min^{-1}. Eq. (8) represents the relationship between rowing performance and fitness level, hence it offers some training directions to rowers. For example, if a rower has a $\dot{V}_{O_{2max}}$ of 5.4 l · min^{-1} and desires to row the middle 1000 m of the race in 3'45", $\dot{V}_{O_{2max}}$ should be increased to 4.9 l · min^{-1}.

In conclusion, the mechanical efficiency of rowing a single scull increased with boat velocity (from 20% at 2 m · s^{-1} to 24% at 4 m · s^{-1}). This increase probably reflects the facts that the fluctuation of boat velocity decreases with boat velocity.

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